Advanced Methodology for Fuel Cycle Analysis

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Requirements for Global Fuel Cycle Development

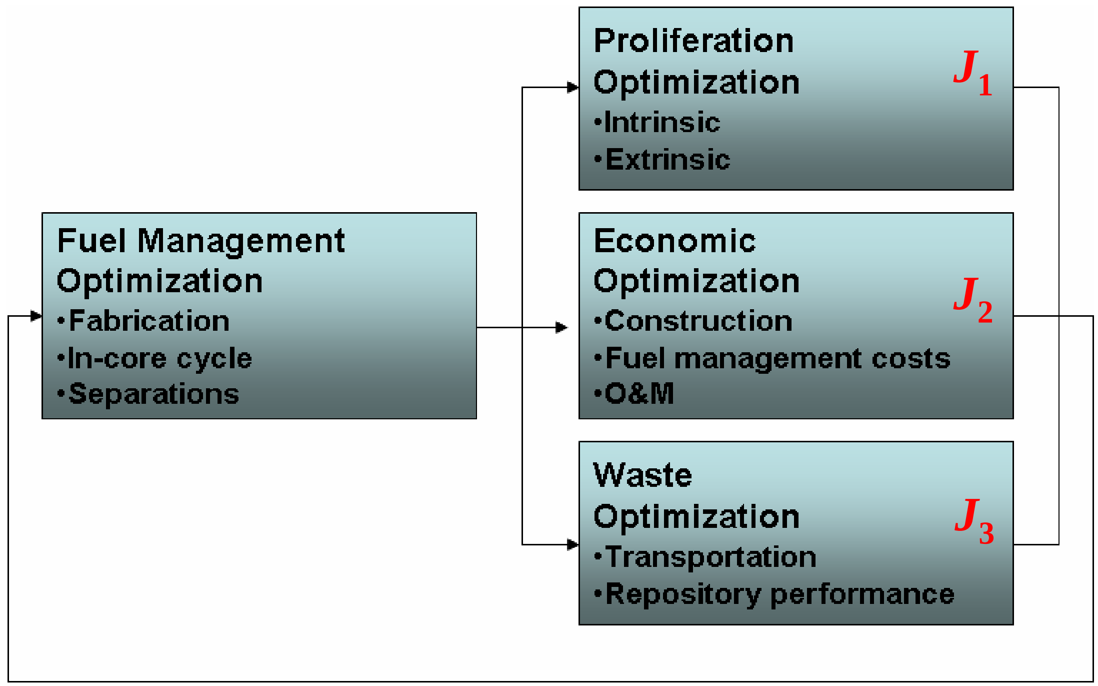
- Generation IV Roadmap goals for fuel cycle optimization
  1. Waste reduction and management
  2. Proliferation risk minimization
  3. Economical fuel cycle and energy production
- Additional Generation IV Roadmap goals
  1. Efficient fuel utilization for sustainable nuclear deployment
  2. Safety, reliability, and plant security
- Approaches for fuel cycle development
  1. Development and optimization of diverse fuel cycle options
  2. Testing and verification of alternate fuel forms
  3. Development of spent fuel reprocessing techniques
  4. Global/regional agreement for nuclear materials safeguards

Overall Fuel Cycle and System Analysis

- Optimize fuel cycle objective function:

$$J = \sum_{i=1}^{3} w_i J_i(x)$$

- Weights w_i balance overall fuel cycle cost.



- Fuel Management optimization generates system states x for use in Proliferation, Economics, and Waste optimizations.

$$x = [m(\mathbf{r},t), f(m), g(m), \ldots]$$

$$m(\mathbf{r},T) = \text{EOC discharge fuel vector}$$

$$f(m) = \text{intrinsic proliferation risk attribute}$$

$$g(m) = \text{waste attribute}$$

Proliferation Risk Calculation

- Intrinsic proliferation risk measures utility as a weapon:

$$p_{\text{int}} = \sum_j u_j(m_j)$$

$$m_j = \text{ intrinsic proliferation attribute } j, \text{ e.g., fissile enrichment, separability}$$

$$u_j = \text{ untility function for proliferation attribute } j$$

- Extrinsic proliferation risk measures, via dynamic event tree, vulnerability through proliferation barriers:

$$p_{risk} = \sum_k p_{ext,k}(p_{\text{int}})c_k$$

$$p_{ext,k} = \text{ probability of penetrating barrier } k$$

$$c_k = \text{ consequence of penetrating barrier } k$$

Intelligence	**Diversion**	**Recovery**	**Weaponization**	**Detection**	**Consequence**

Proliferation sequence

- Evaluate J_1 as time integral of p_{risk} and/or at the most limiting process and time.

Limit Surface and Proliferation Risk Quantification

- Obtain system state **x** for acceptable proliferation risk in terms of risk-significant attributes, e.g., fissile enrichment:

$$g(\mathbf{x},t) < g_{\max},\ t \in \text{mission time}$$

$$\Rightarrow \text{ limit surface } = \{\mathbf{y} = h(\mathbf{x}) \mid g(\mathbf{x},t) = g_{\max}\}$$

- Determine proliferation risk for the system, at the most limiting point in the system performance, with uncertainty represented through pdf $f(\mathbf{x})$:

$$p_{\text{risk}} = \int [g(\mathbf{x}) - g_{\max}]\, f(\mathbf{x})\, d\mathbf{x};\ g(\mathbf{x}) > g_{\max}$$

- Limit surface may be mapped through Alternating Conditional Expectation algorithm.
- ACE performs *conditional* regression of independent variables x and dependent variable y iteratively to obtain optimal transformations $\theta(y) = \phi(x)$, with local variation represented by $\phi(x)$ and global variation by $\theta(y)$.

Spent Nuclear Fuel Management

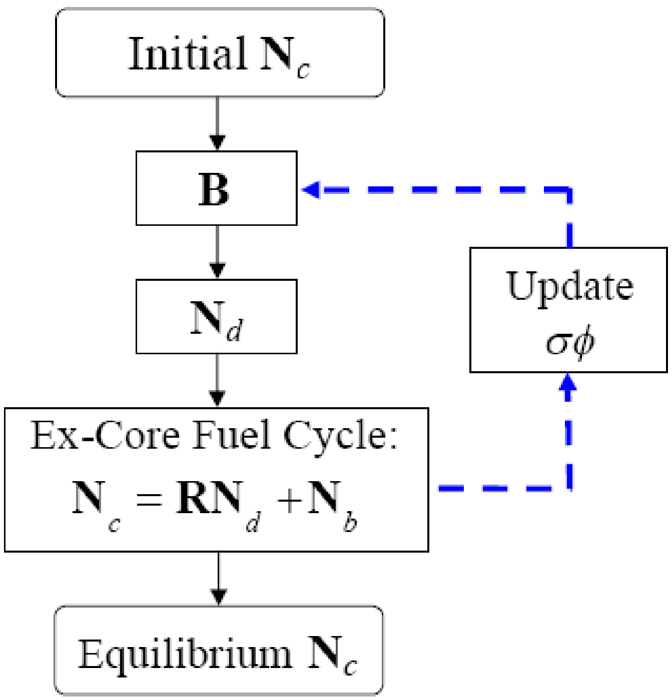
- Open and closed fuel cycles
  1. Once-through LWR uranium cycles
  2. One recycle of spent fuel Pu in MOX:
     MA/FP vitrified and discharged MOX fuel in storage
  3. Multi-tier thermal and fast reactor cycles
  4. Alternate fuel forms for multiple LWR recycles:
     $(Th\text{-}Pu)O_2$ for enhanced Pu/TRU transmutation

- Impacts of P/T of spent fuel
  1. Reduction in waste volume
  2. Economic penalty: >$1,000 per kg HM reprocessing
  3. Increased proliferation risk

- Optimal fuel cycle: balance between proliferation risk reduction and other goals

LWR Equilibrium Cycle for Fuel Management

LWR Equilibrium Cycle Methodology



Microscopic reaction rates comprising **B** are iterated until **B** and $\mathbf{N}_c$ converge

- Equilibrium cycle is calculated for direct comparison between different reactor designs.

  N_c: charge vector

  N_d: discharge vector

  N_b: blend down vector

  $N_d = BN_c$

  B = transmutation matrix

  R = reprocessing matrix

- Minimize objective function y set to total EOC fissile inventory:

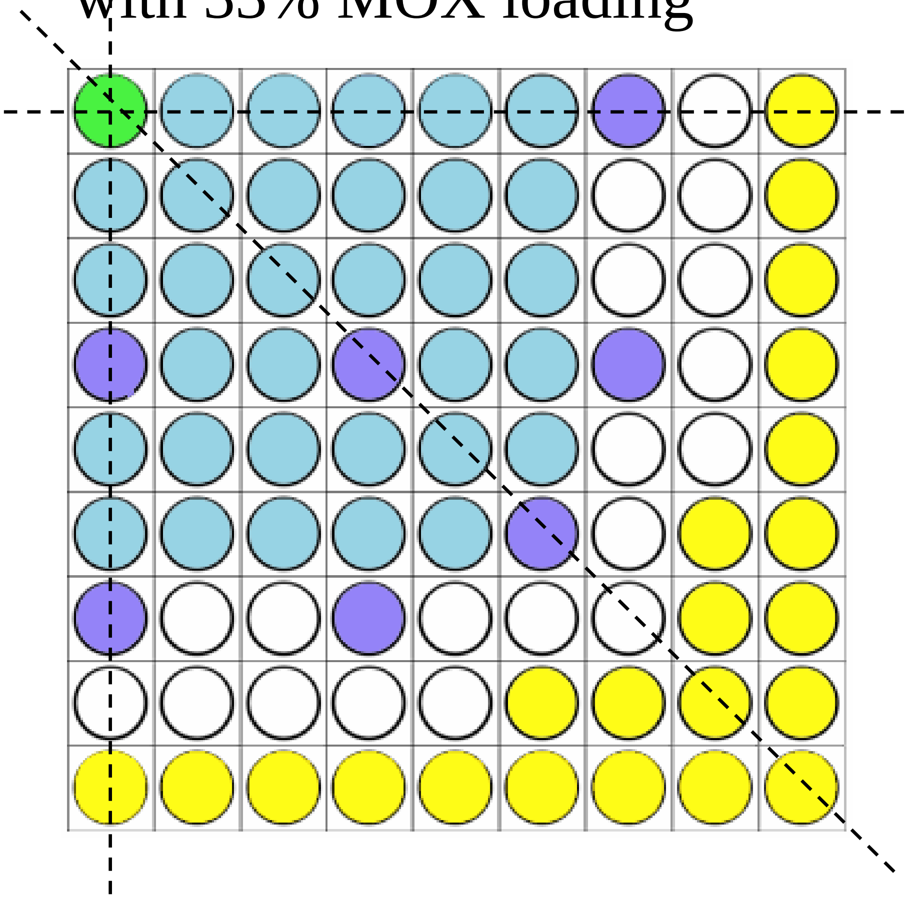
  $$\min\left\{y = \int_V m(\mathbf{r},T)\,d\mathbf{r}\right\}$$

  subject to the power peaking constraint $p(\mathbf{r},t) \le p_{\max}$

Alternate LWR Cycle: Th-Pu MOX as an Example

Thorium-Based **M**ixed-**O**xide (**TMOX**) Assembly

Standard 17x17 PWR assembly with 33% MOX loading



- Natural Th serves as the host for Pu in the MOX
- TMOX not only stabilizes Pu inventory, but consumes Pu
- Denaturing Th with ^{238}U reduces ^{233}U proliferation risk

$(Th,^{233}U)O_2$ + Er Pin

$(Th,^{233}U)O_2$

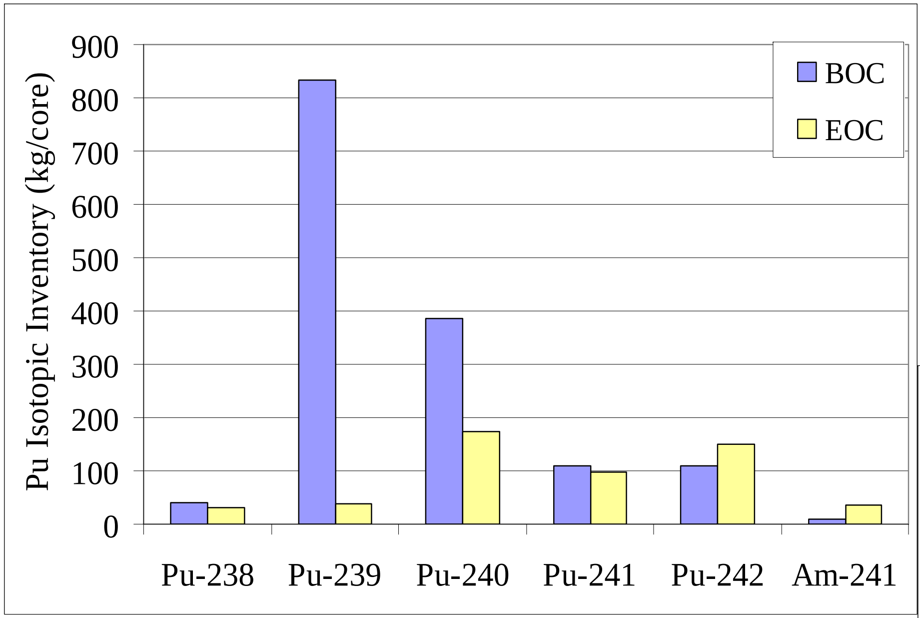
$(Th,Pu)O_2$ MOX Pin

Guide Tube (GT)

Instrument Tube (IT)

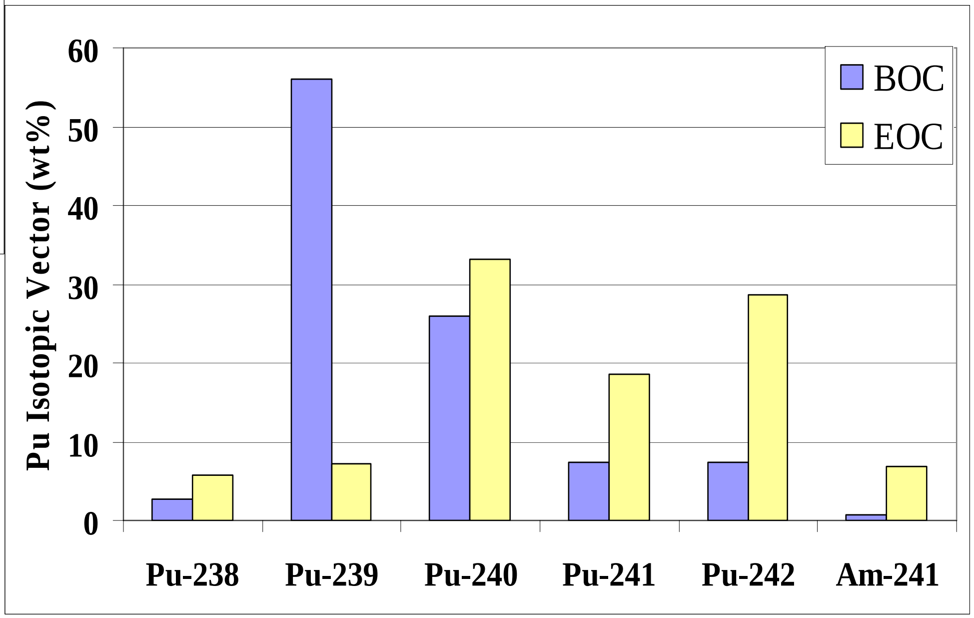
Once-Through TMOX Pu Destruction Capability

Pu Isotopic Inventory



95 % ^{239}Pu destruction
and
70 % total Pu destruction

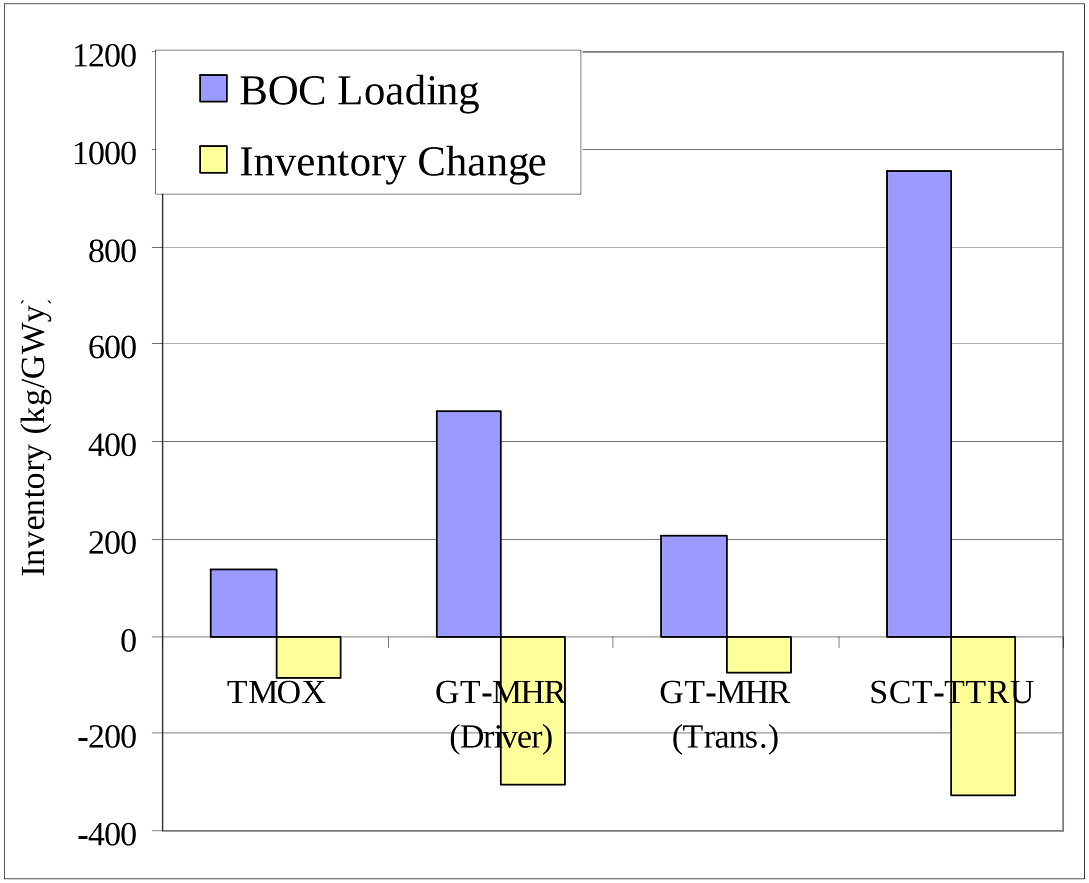
Pu Isotopic Vector



With **Zero** ^{239}Pu production, TMOX allows for a deep burn of the initial Pu loading, rendering it useless for weapons proliferation.

TRU Recycling Comparison

BOC TRU loading and depletion

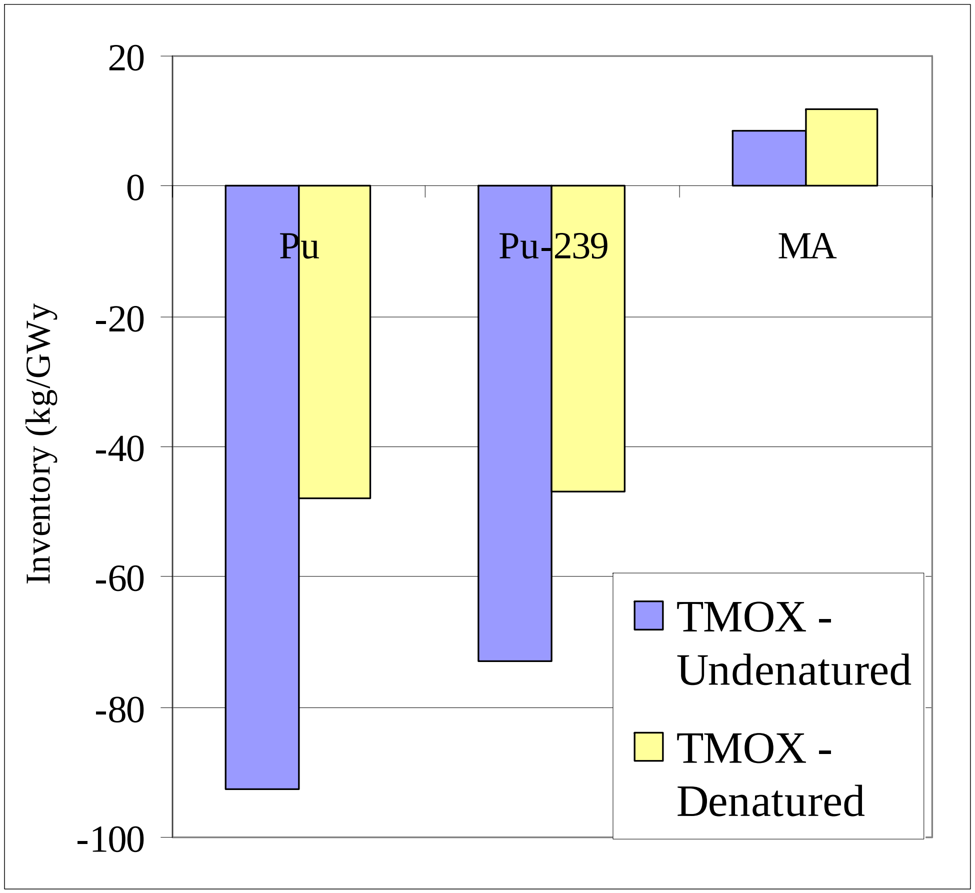


TRU = Np + Pu + Am + Cm

- UMOX: Net production of Pu
- By not using ^{238}U, the TMOX configuration destroys approximately the **SAME** amount of Pu produced in the current UO_2 fuel cycle!
- GT-MHR: 98% fractional ^{239}Pu depletion; 70% fraction Pu depletion.
- GT-MHR requires an additional separation step for the transmutation fuel.
- Th-based fuel in fast reactor accommodates full TRU vector.

Effect of Denaturing on TMOX Performance

Net Change in Inventory



- Additions of natural U deteriorate the Pu depletion capability.
- Natural U also leads to a larger MA production.
- Need to develop denaturing strategies that will mitigate the proliferation concern of ^{233}U without having to compromise Pu depletion.

Sacrifice Pu depletion and waste reduction for proliferation resistance

Computational Requirements for Fuel Cycle Optimization

- Need to optimize the entire fuel cycle, satisfying goals for minimizing proliferation risk, repository burden, and economics, in addition to traditional incore fuel management.
- Denatured TMOX cycle illustrates that the optimization task has to resolve conflicting objectives, e.g., TRU depletion and minimizing proliferation risk.
- Significant improvements to DANESS and NFCSim are necessary to perform realistic optimization of incore and excore processes and repository performance.
- Proliferation risk quantification and repository performance assessment via limit surface, representing a dynamic event tree for back-end fuel cycle, is similar to the NUREG-1150 severe accident assessment task.